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... for a brighter future

Tutorial on
Agent-based Modeling and Simulation

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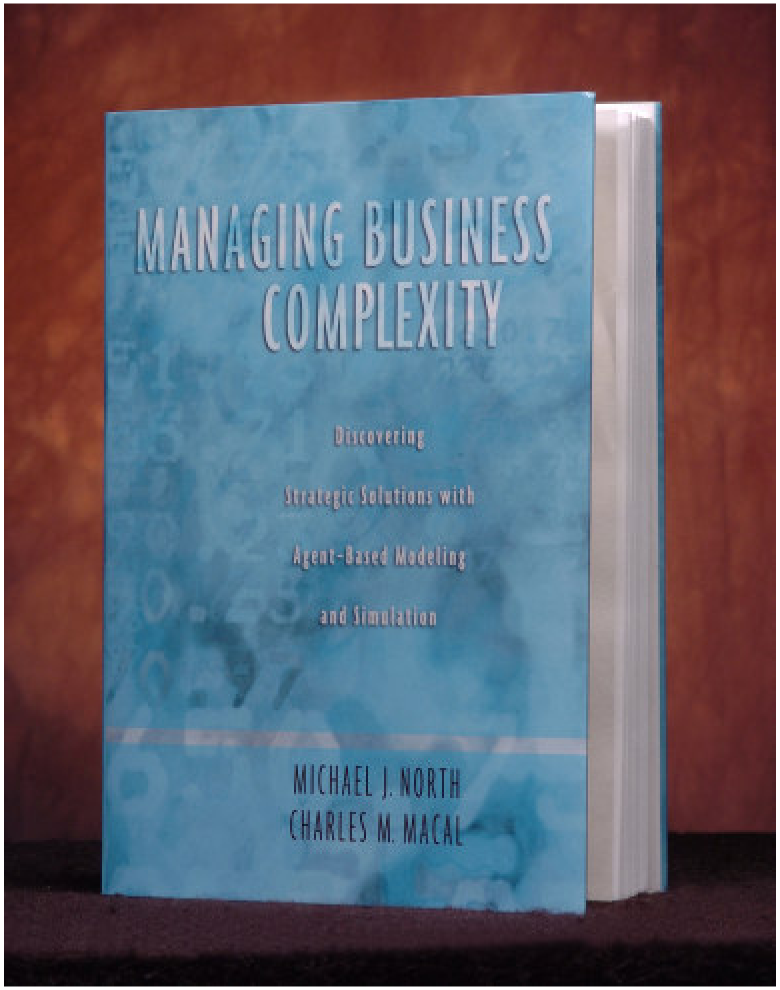
Tutorial on Agent-based Modeling and Simulation

- **Presentation Goals**
  - How to think about agent-based modeling and simulation (ABMS) and agents
  - How to do ABMS
  - Explain how ABMS is *Useful, Usable, and Used!*

- **Outline**
  1. **Background**: What it is and where did ABMS come from?
  2. **Applications** of Agent-Based Models
  3. **How To** do Agent-Based Modeling

For more information on agent-based modeling please see *Managing Business Complexity: Discovering Strategic Solutions with Agent-Based Modeling and Simulation* (Oxford 2007)



Background

Where Did ABMS Come From?

The "Name Game"

- ABMS is known by many names:
  - ABM: "Agent-based modeling" or "anti-ballistic missile?"
  - ABS: "Agent-based simulation" or "anti-lock brakes?"
  - IBM: "Individual-based modeling" or "International Business Machines Corporation?"
- ABM, ABS, and IBM are all widely-used acronyms, but "ABMS" will be used throughout this discussion
- ABMS is not the same as "mobile agents"

The Need for Agent-based Modeling

We live in an increasingly complex world.

- **Systems More Complex**
  - Systems that need to be analyzed are becoming more complex
  - Decentralization of Decision-Making: “Deregulated” electric power industry
  - Systems Approaching Design Limits: Transportation networks
  - Increasing Physical and Economic Interdependencies: infrastructures (electricity, natural gas, telecommunications)
- **New Tools, Toolkits, Modeling Approaches**
  - Some systems have always been complex, but tools did not exist to analyze them
  - Economic markets and the diversity among economic agents
  - Social systems, social networks
- **Data**
  - Data now organized into databases at finer levels of granularity (micro-data) – can now support micro-simulations
- **Computational Power**
  - Computational power advancing – can now support micro-simulations

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Agent-based Simulation Is a New Field Grounded in the Biological, Social, and Other Sciences

- What is an agent?
  - A discrete entity with its own goals and behaviors
  - Autonomous, or self-directed, with a capability to adapt and modify its behaviors
- Assumptions
  - Some key aspect of behaviors can be described.
  - Mechanisms by which agents interact can be described.
  - Complex social processes and a system can be built “from the bottom up.”
- Examples
  - People, groups, organizations
  - Social insects, swarms
  - Robots, systems of collaborating robots
- Agents are diverse and heterogeneous

Agent-based Modeling Is Related to Many Fields

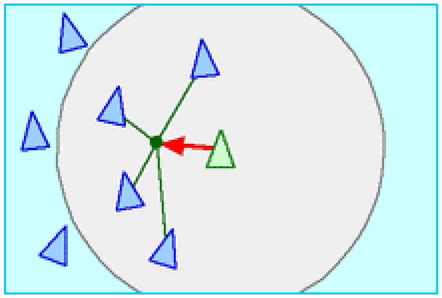
- ABMS is most closely related to Complex Adaptive Systems (CAS)
  - Complexity Science
  - Network Science
- Systems Science: Systems Dynamics
- Traditional Simulation and Operations Research
  - Discrete Event Simulation
  - Optimization

What is an agent model?

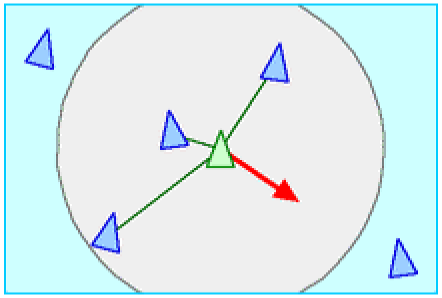
What Is Agent-Based M&S?

- An agent-based model consists of:
  - A set of agents (part of the user-defined model)
  - A set of agent relationships (part of the user-defined model)
  - A framework for simulating agent behaviors and interactions (provided by an ABMS toolkit or other implementation)
- Unlike other modeling approaches, agent-based modeling begins and ends with the agent's perspective

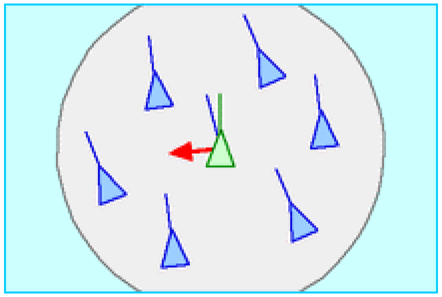
Reynold's Boids' Model: Simple Schooling/Flocking Behavior with Agent Rules



Cohesion:
Steer to move toward the average position of local flockmates

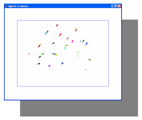


Separation:
Steer to avoid crowding local flockmates



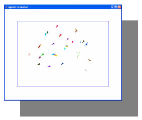
Alignment:
Steer towards the average heading of local flockmates

Source: "Boids" by Craig Reynolds, http://www.red3d.com/cwr/boids/

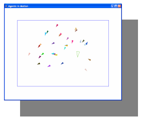


Some Questions About Reynold's Boids Model

- What do we anticipate to be the behavior of the agents as they operate according to these simple rules described above?
- Will the agents randomly mill around, stand still, or exhibit other behavior?
- How can we characterize the behavior of the agents that we visually observe during the simulation?



Demonstration: Reynold's Boids Model

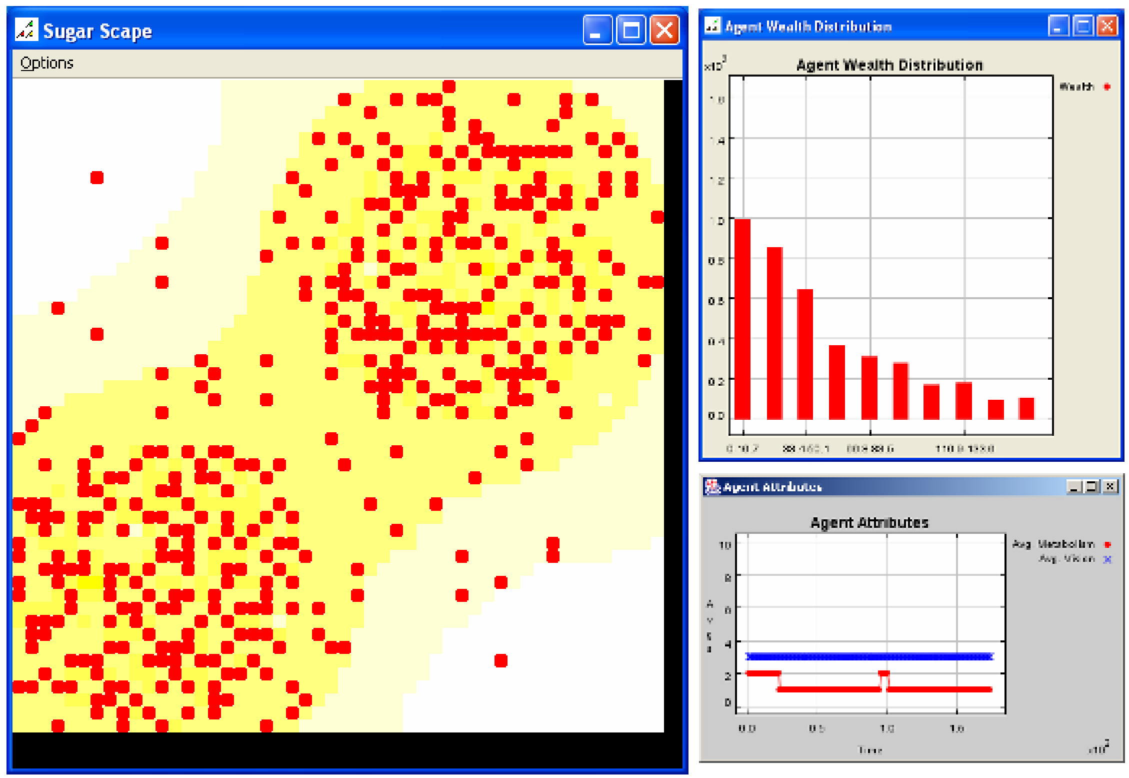


Emergence: A Key Result of Agent-based Simulation

- Agent-based systems may exhibit sustainable patterns, structure, and organization at the system level, that are not programmed into the behaviors of the individual agents
- Emergent patterns are solely the result of agent rules and interactions operating on a localized basis

Epstein and Axtell's "Sugarscape" Was the First Comprehensive Computational Model Used to Study Artificial Societies

***Sugarscape* agents have…**
- **Life, Death, Disease**
- **Trade: Sugar, Spice**
- **Wealth**
- **Sex, Reproduction**
- **Culture**
- **Conflict, War**
- **Externalities: Pollution**

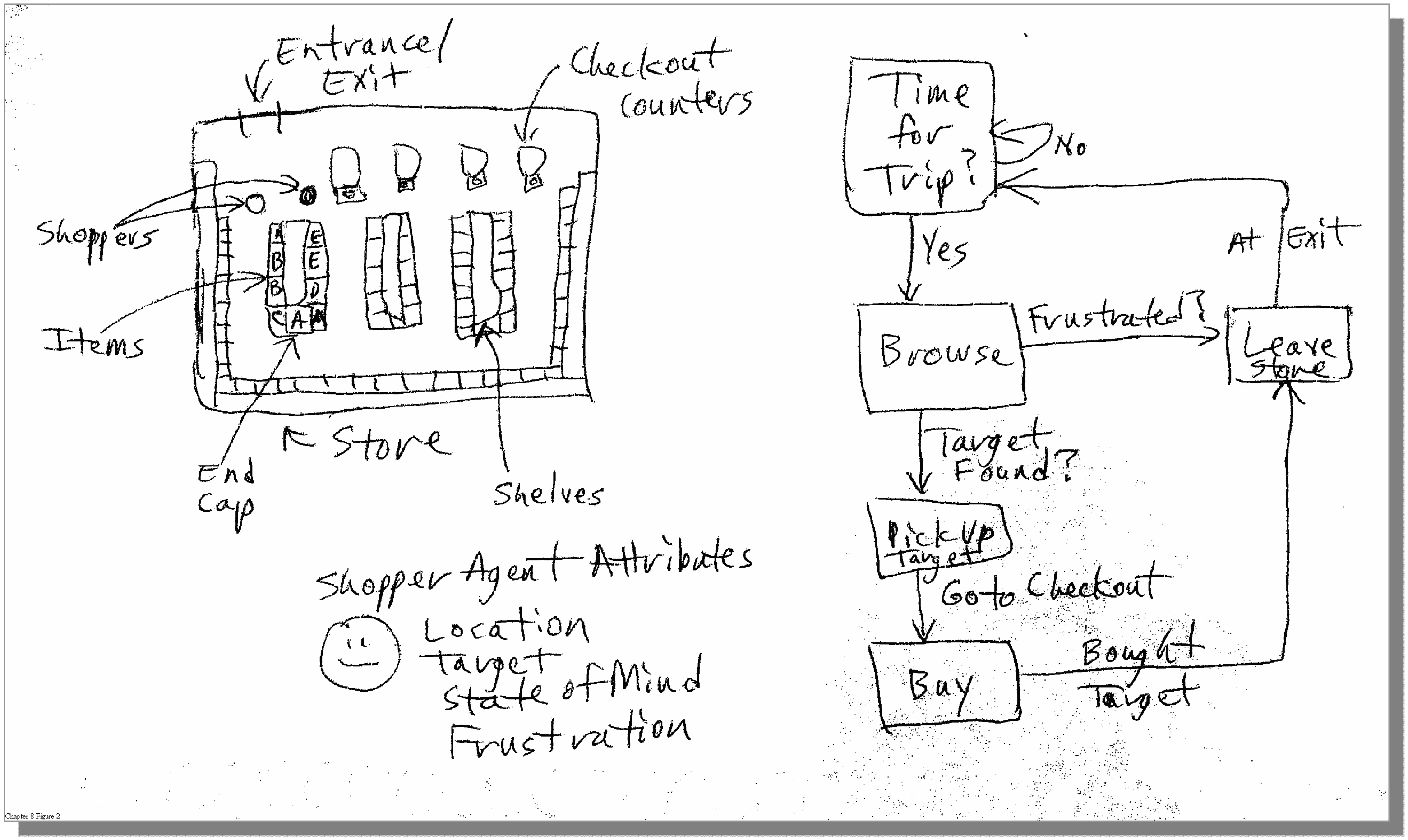


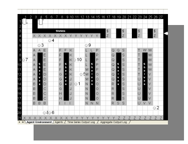
Results from Repast simulation of Sugarscape model.

Source: Epstein JM, Axtell R. 1996. Growing Artificial Societies: Social Science from the Bottom Up. Cambridge, Mass.: MIT Press

Desktop ABMS: An Agent-based Model Example

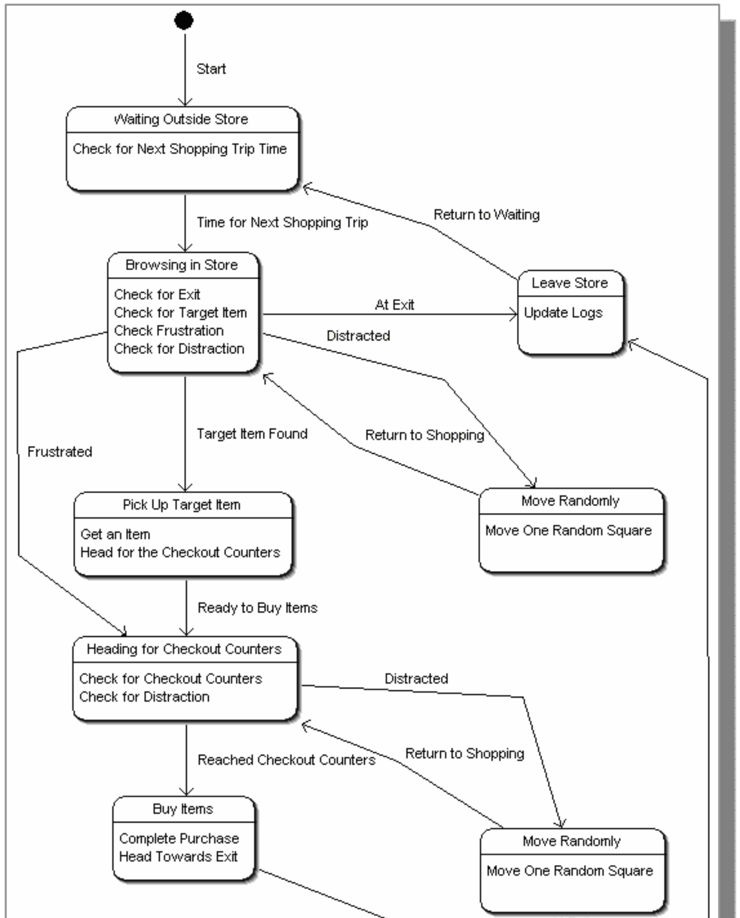
A model of shopper behavior in a grocery store:



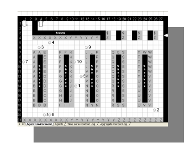


Agent Behaviors Are Represented by Rules and Expressed in Flowcharts

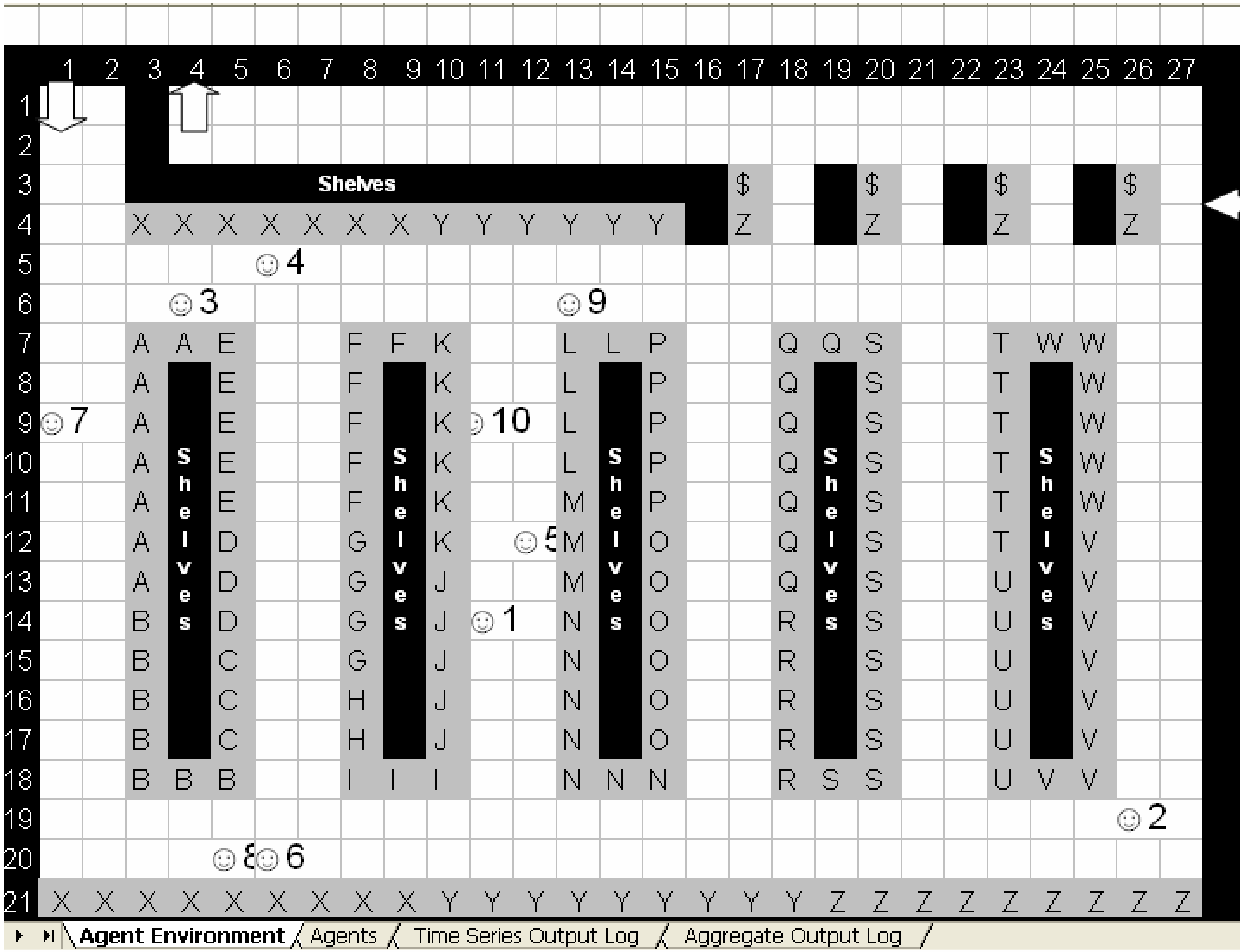
- Shopper agent in the grocery store:

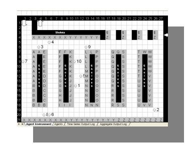


Chapter 8 Figure 5



Demonstration: Grocery Store Simulation



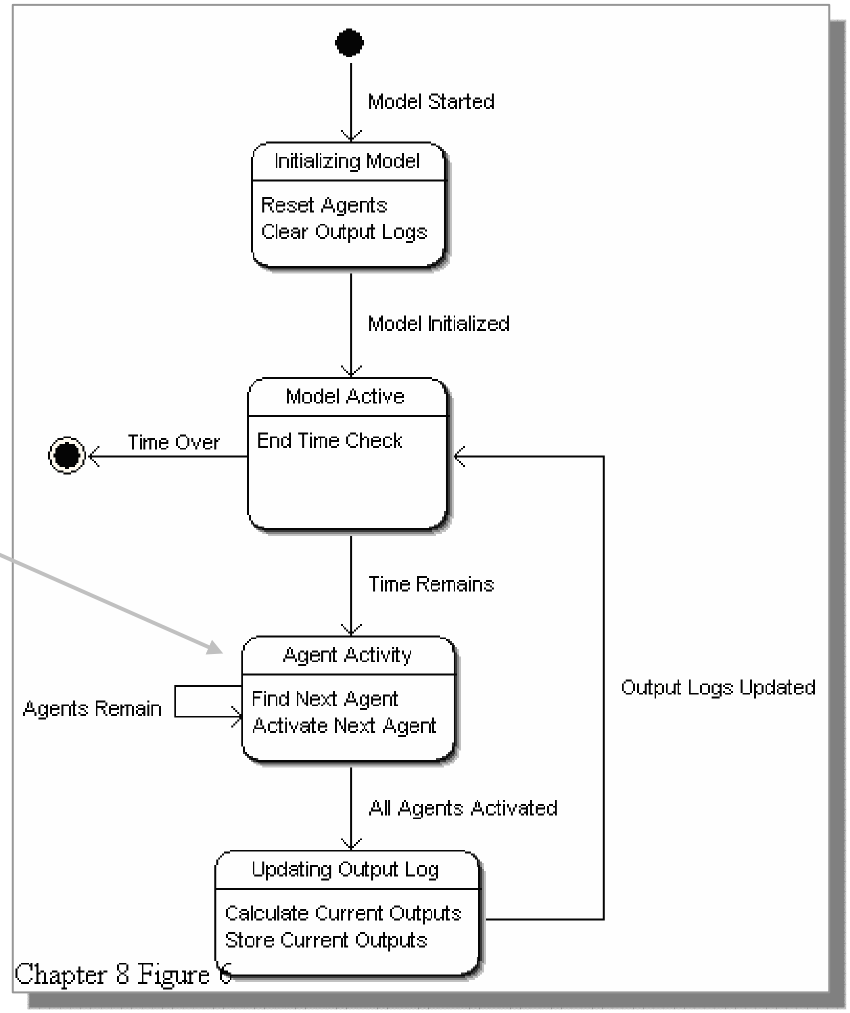


C:\Documents and Settings\macal\My Documents\PAPERS\2006-11-05-06-Pres-INFORMS 2006-ABMS Tutorial(Pittsburgh)

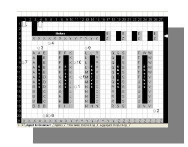
Agent Activity Is Embedded in the Agent Simulation

Shopper Agent Activity

1. Select which agent moves next
2. Activate agent's behavior



Chapter 8 Figure 6



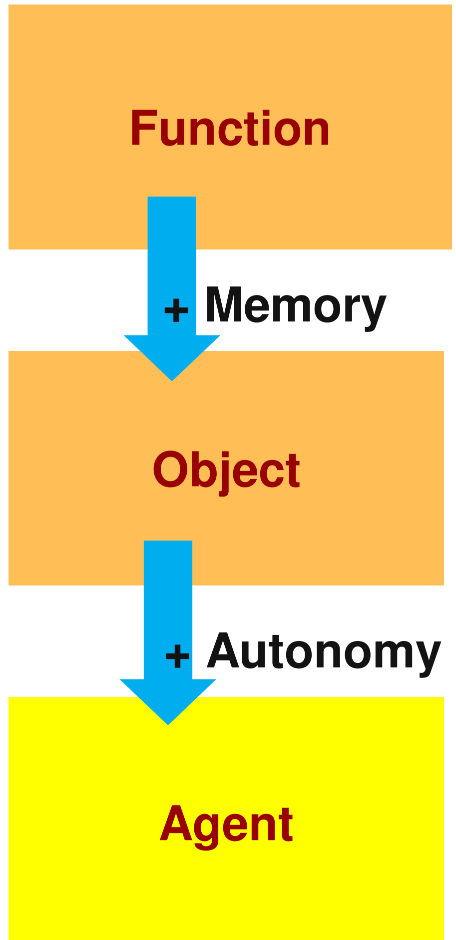
What Is An Agent? Agents Are Autonomous Decision-making Units with Diverse Characteristics (Heterogeneous)

- **Decision rules vary by agent**
  - Sophistication of rules
  - Cognitive "load"
  - Internal models of the external world
  - Memory employed

- **Agents vary by their attributes and available accumulated resources**

- **What is the effect of agent diversity on the system?**
  - Do certain types of agents dominate?
  - Does the system evolve toward a stable mix of agent types?

What Is an "Agent?"



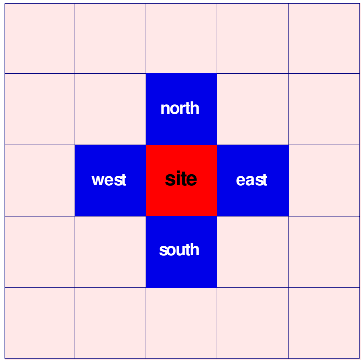
Agent Simulation Is Based on "Local" Interaction Among Agents

- No central authority or controller exists for:
  - How the system operates
  - How the system is modeled
  - How the system/model moves from state to state
- "Optimization" can be done for the system as a whole

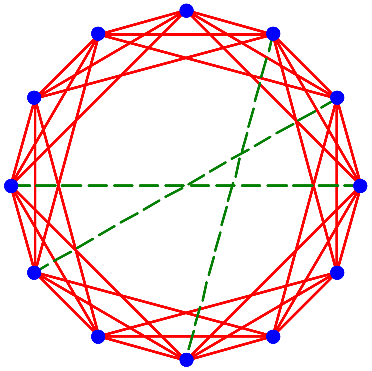
Agents Have Neighborhoods

Various Topologies Connect Agents with Agents in Their Neighbors

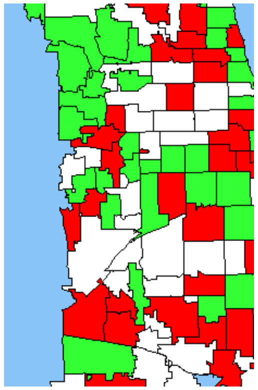
- Cellular automata have agents interacting in local “neighborhoods”
- Networks are general representations of agent interaction
- Free (continuous) space
- Geographical Information Systems (GIS) tilings
- Sometimes *spatial* interactions are not important (“Soup” Model)



von Neumann neighborhood



Small World Network

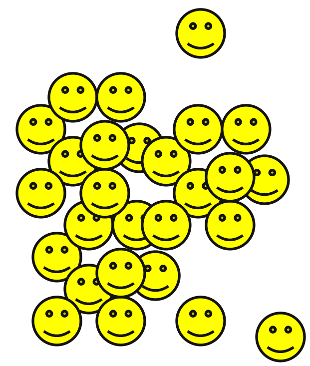


GIS

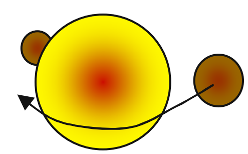
How does agent modeling compare to traditional modeling techniques?

How Does ABMS Compare to Traditional Modeling Techniques? (1 of 3)

- ABMS represents systems from the ground up using individual-level rules:
  - Top Strength: Tying together micro-level behavior with macro level effects
  - Top Weakness: A significant number of details may be required to properly represent systems and the resulting model may be stochastic
  - We will see that ABMS is complementary to traditional modeling techniques…

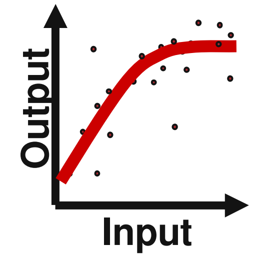


- Analytical modeling seeks to develop rigorous, provable statements about systems:
  - Top Strength: The results are certain
  - Top Weakness: “Heroic” assumptions are required to represent most real world problems, if they can be represented at all
  - Complimentary to ABMS: Can bound system and agent behaviors

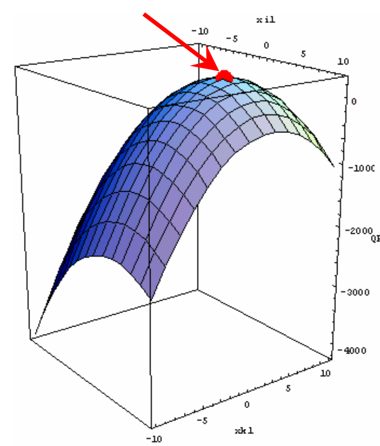


How Does ABMS Compare to Traditional Modeling Techniques? (2 of 3)

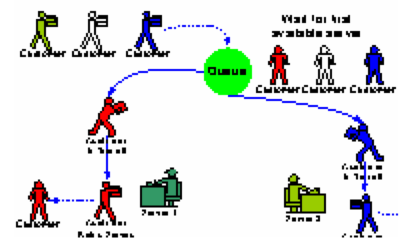
- Statistical modeling rigorously specifies how outputs depend on inputs:
  - Top Strength: The uncertainty in the results is rigorously bounded
  - Top Weakness: Systems are represented as a “black boxes,” with little explanation of why things happen and limited ability to extrapolate
  - Complimentary to ABMS: Can analyze inputs and outputs



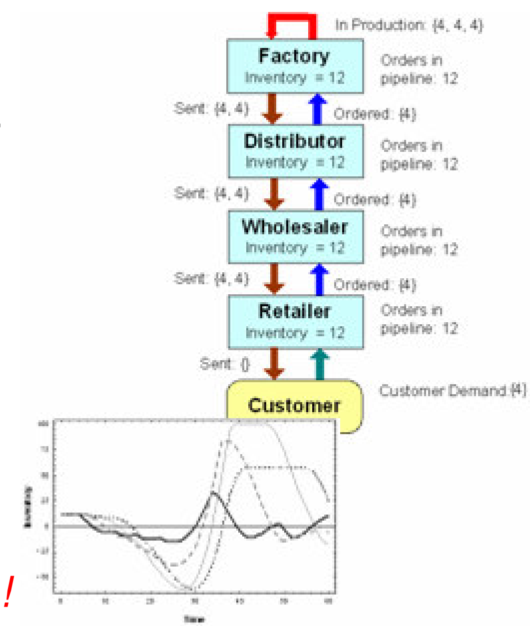
- Optimization modeling seeks to find optimal solutions relative to well-defined objectives and subject to specific constraints:
  - Top strength: “Best” solutions are found
  - Top weakness: “Best” is often ambiguous and solutions can lack robustness
  - Complimentary to ABMS: Can provide agent behaviors and drive parameter sweeps



How Does ABMS Compare to Traditional Modeling Techniques? (3 of 3)



- Discrete event simulation represents the inner workings of dynamic processes and moves those representations forward through time at a system level:
  - Top strength: Able to model many situations
  - Top weakness: Top-down orientation with a focus on system-level rules
  - Complimentary to ABMS: Can provide time management



- Systems dynamics modeling represents processes as flows over specialized networks:
  - Top strength: Clear and simple system-level specifications
  - Top weakness: Limited ability to represent complicated, heterogonous, and individual processes
  - Complimentary to ABMS: Can provide agent behaviors and bound system behavior

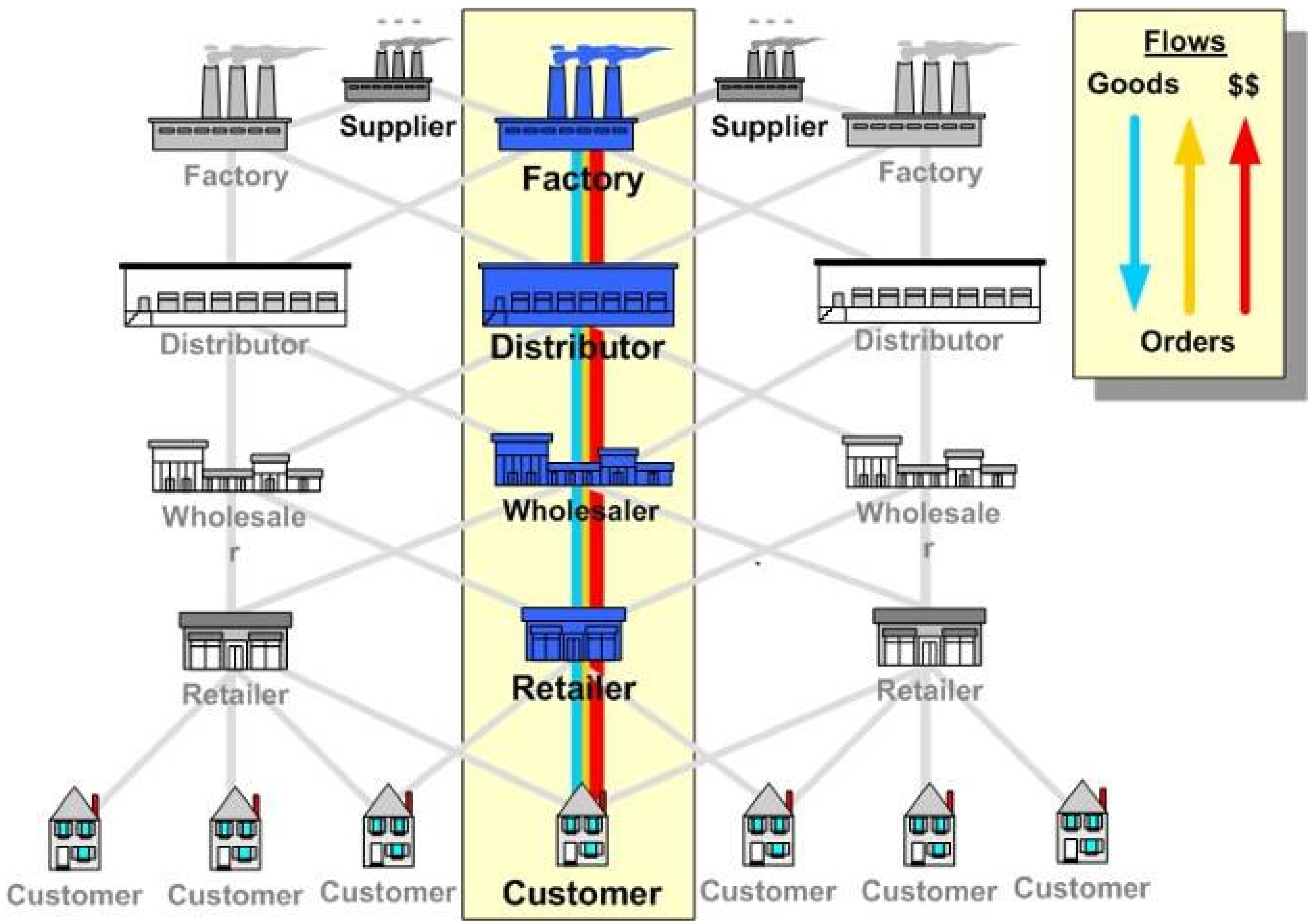
*The conclusion is that ABMS is **complimentary** to other techniques!*

Applications of agent-based models

Agent-Based Simulation Is Actively Being Applied in Many Areas

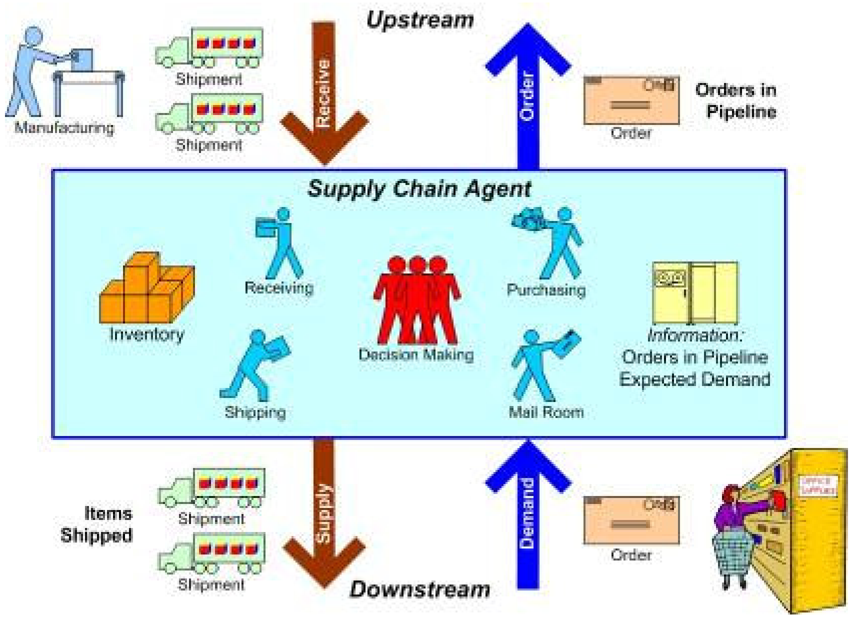
- Economics
  - Trade, Market Structures
  - Financial Markets
- Organizations, Business
  - Manufacturing, Operations
- Supply Chains
- Electric Power Market Restructuring
- Hydrogen Economy
- Transportation
- Human Movement
  - Evacuation Modeling
- Societies, Cultures
- Terrorism
  - Social determinants
  - Functional structures
- Military
  - Command & Control
  - Force-on-force
- Consumer Markets
- Biological Processes
  - Ecology
  - Animal Group Behavior
  - Cell Behavior
  - Sub cellular Networks

ABMS Application to Supply Chains

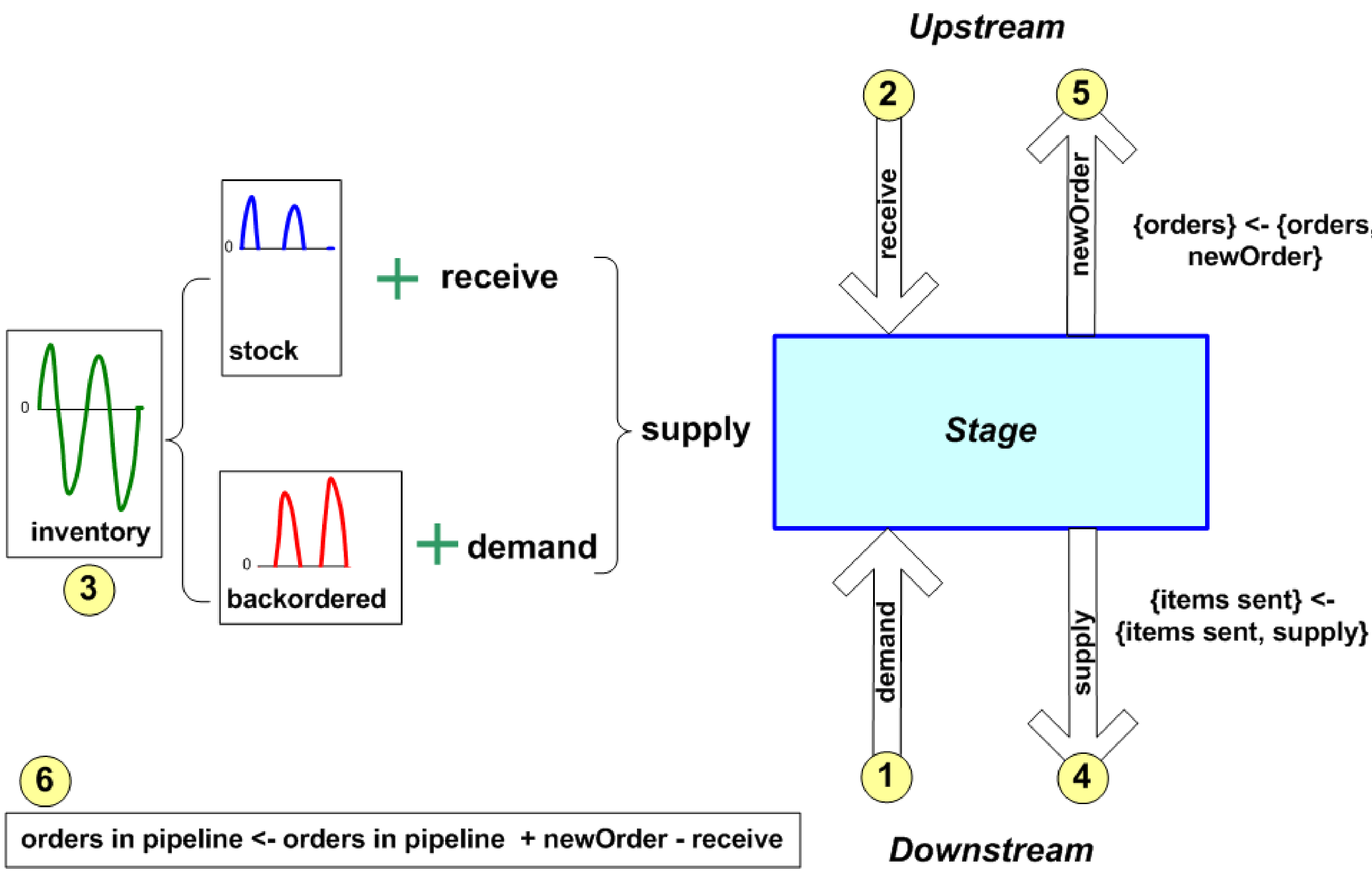


The World of the Supply Chain "Agent"

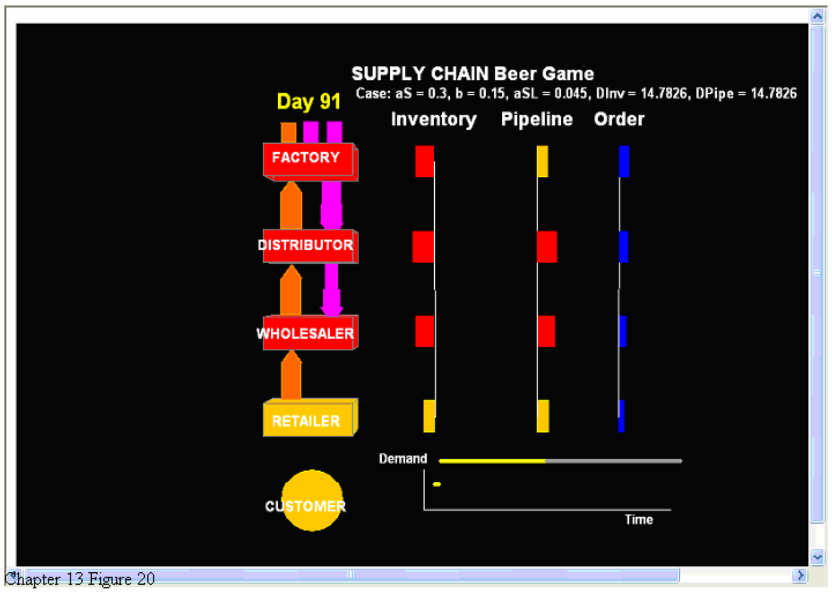
- What will be tomorrow's demand?
  - Demand Forecasting Rule
- How much to order?
  - Ordering Rule
  - From who?
- How much to ship?
  - Shipping Rule
  - To who?
- How to organize these decisions?
  - Business Process

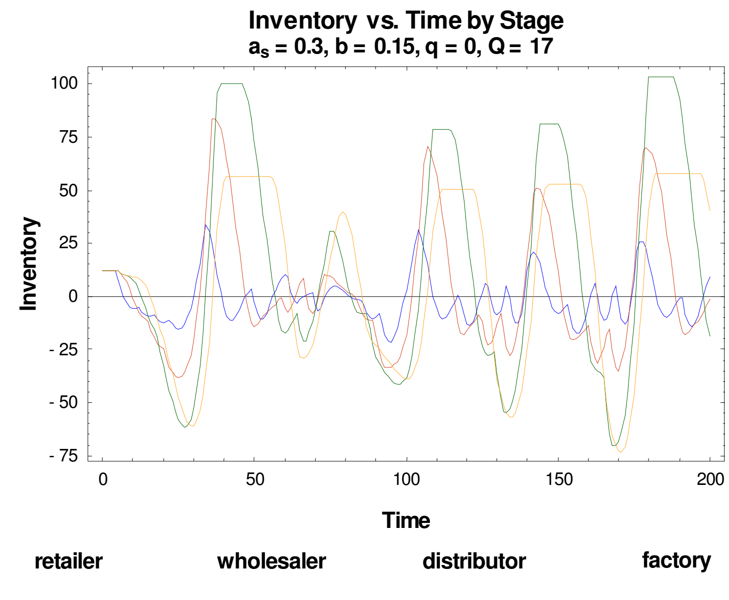


Agent Logic Applied Each Period



Demonstration: Supply Chain Model

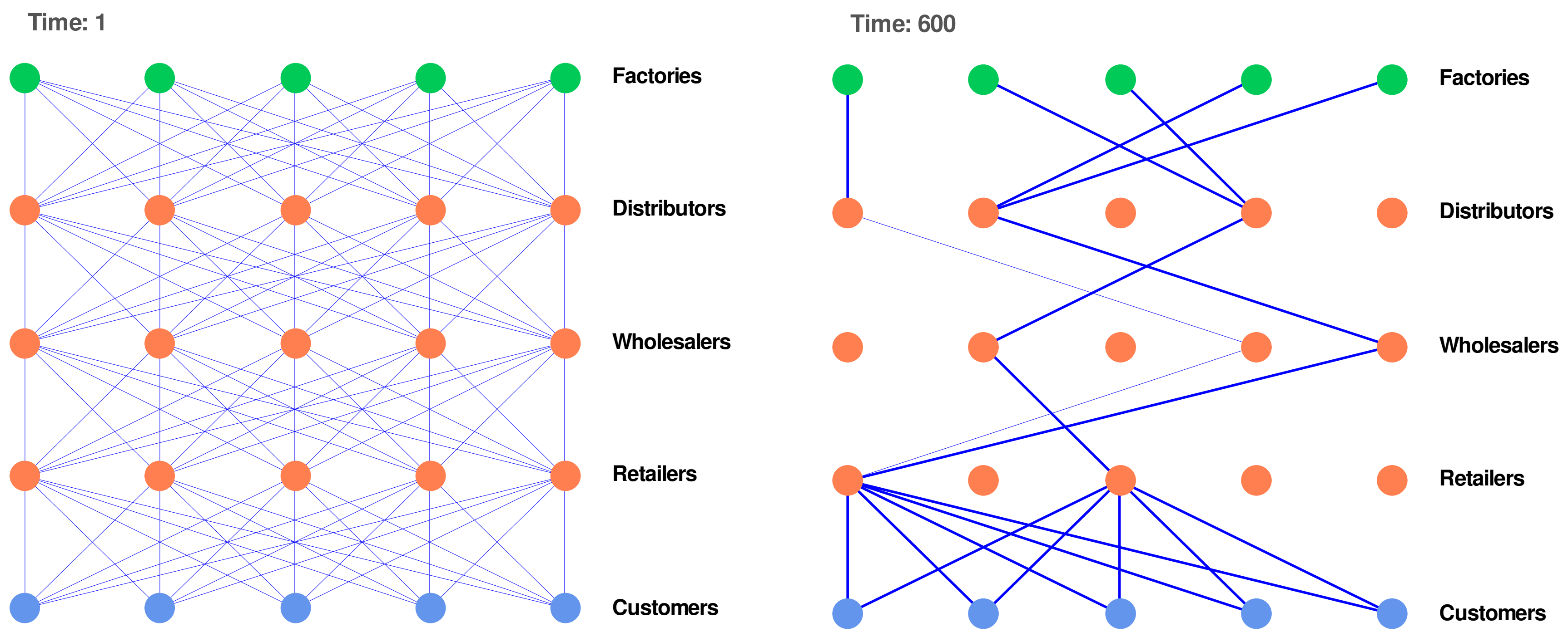




Agent-based modeling is uniquely capable of easily modeling the range of alternative agent decision rules

- We can consider non-traditional factors in supply chain agent decision problems
  - Behavioral factors
  - Social factors
- We consider basing supply chain agent decisions on trust and the establishment of sustaining relationships
- Action/Reaction basis of establishing trust
  - Trust is increased if suppliers consistently fill orders on time
  - Trust is decreased otherwise

Supply Chain Trust Simulation



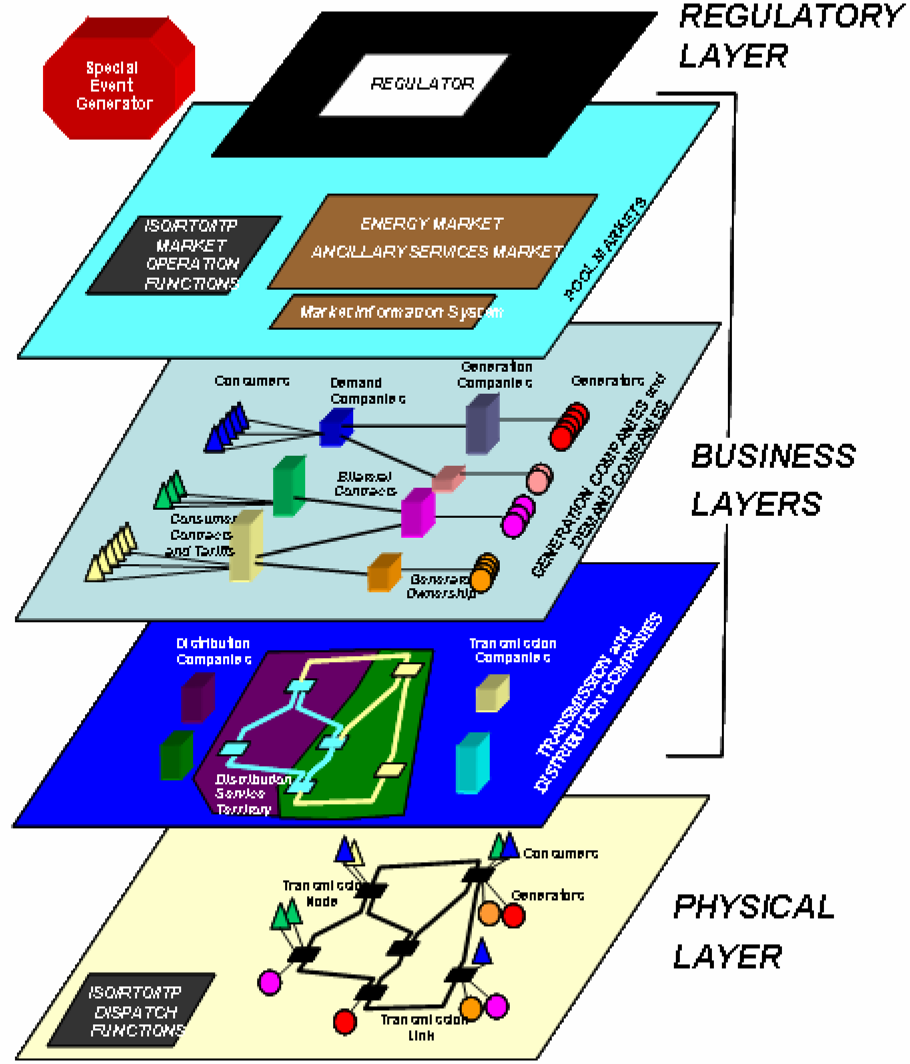
- After 600 periods, agents have developed sustainable relationships with some supply chain partners based on the history of their relationships (trust)

ABMS Application to Electric Power Systems

- Until recently, most electric power systems where managed by regulated, vertically integrated monopolies
- Several systems, such those in California and Brittan, have implemented open markets that seek to promote competition among suppliers and provide consumers with a choice of services
- In the old systems, decision-making was centralized within the managing monopolies:
  – Most power systems analysis models developed over the last three decades are based on the implicit assumption of a centralized decision-making process
  – Argonne has developed these types of models and has applied them to analyze conventional electric systems for over thirty years
  – These models are often very detailed and will continue to provide many useful insights
- However, in deregulated systems decision-making is distributed among many competing organizations:
  – Unfortunately, the old models are limited in their ability to adequately analyze markets with decentralized decision-making
  – Argonne's Electricity Market Complex Adaptive Systems (EMCAS) model explicitly addresses decentralized decision-making using CAS and ABMS…

The Electricity Market CAS Model (EMCAS) Applies ABMS to Model Decentralized Electricity Markets

- EMCAS is an agent-based electricity market model
- EMCAS models the roles of market participants:
  - Generation Companies
  - Demand Companies
  - Consumers
  - Regulators
  - System Operators
  - …
- The agents operate in multiple layers within nested time scales

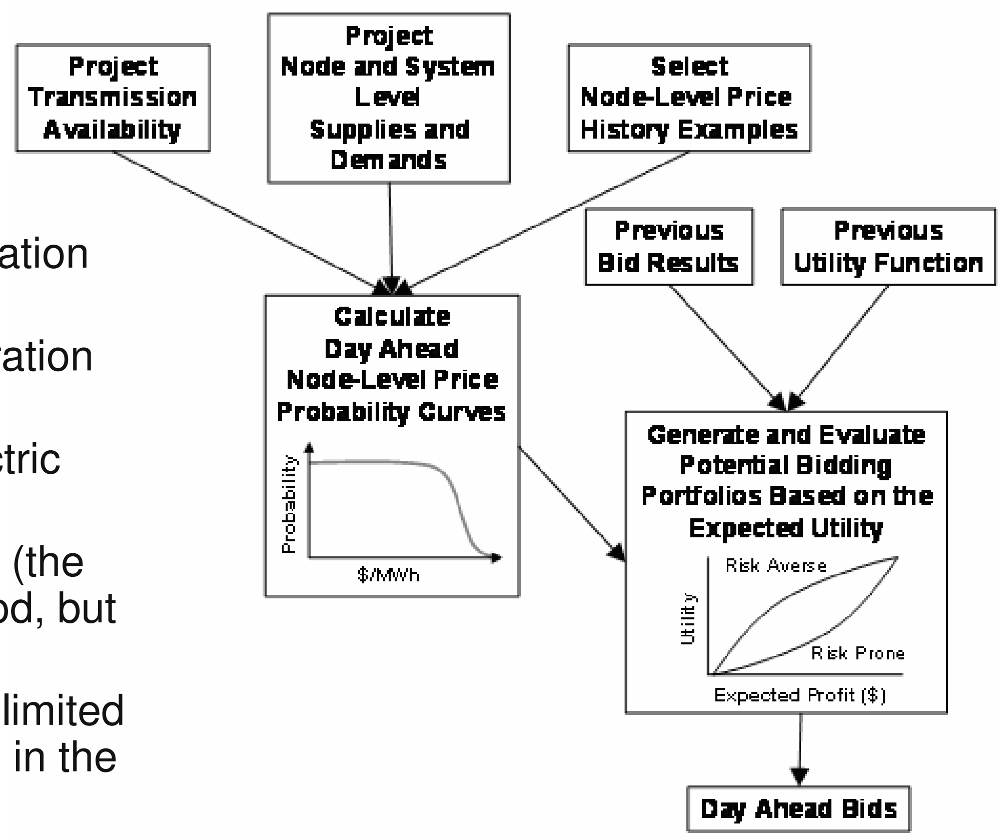


EMCAS is Design to Discover Possibilities

- ECMAS is intended to provide ranges of *possibilities* rather than “point answers:”
  - The ranges of possibilities are created through large numbers of stochastic runs
  - The ranges are intended to discover potential weaknesses in electricity markets rather than say whether or not a given agent (company) will actually exploit a given weakness
- These results can be used by decision makers to form better market policies and make better choices in markets
- These results depend on complex factors such as:
  - Consumer choices
  - Corporate choices
  - Regulatory influences
  - Physical laws

EMCAS Generation Company Agents Use a Sophisticated Decision-Making Process Since Real "GenCo's" Face a Difficult Situation

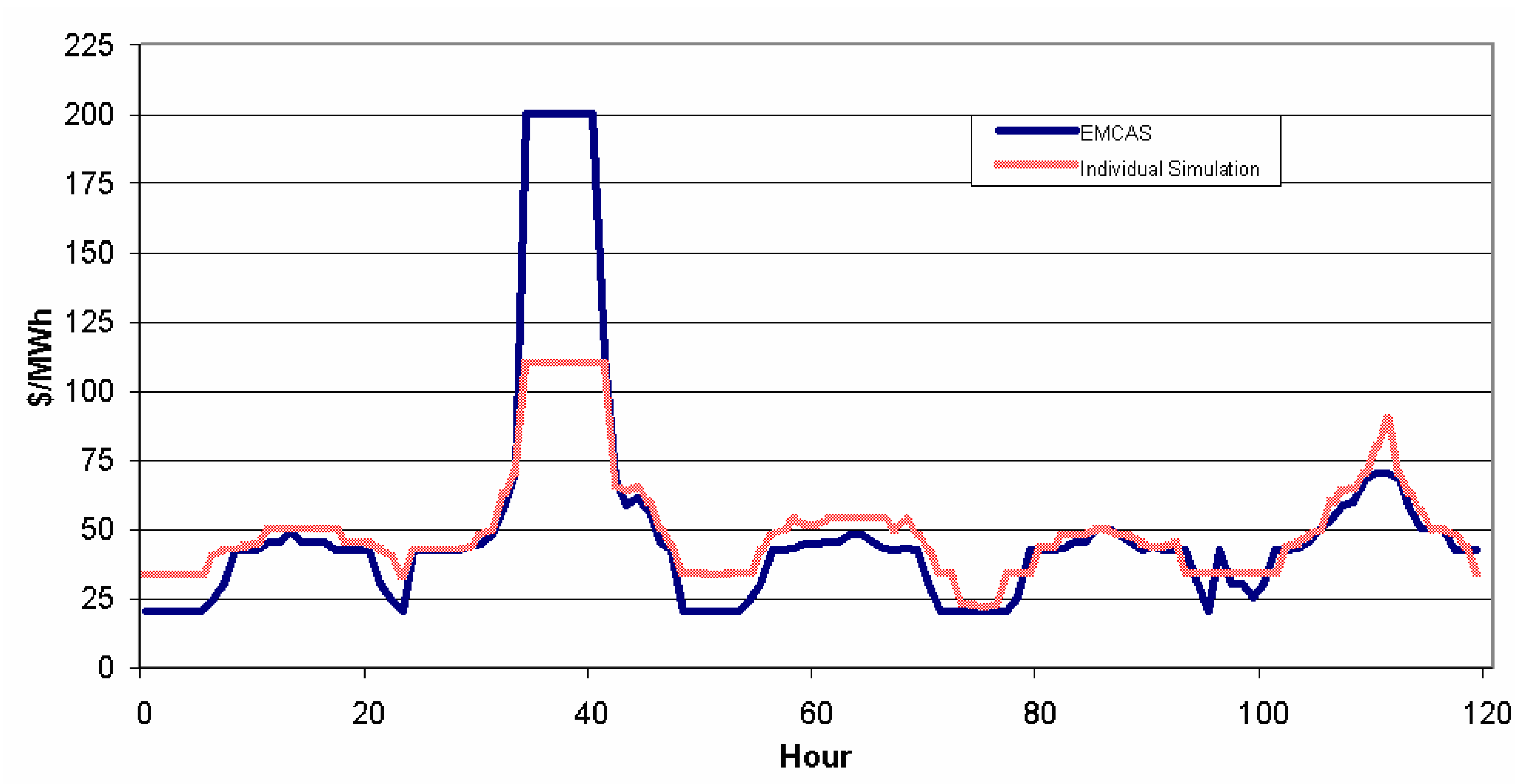
- Generation company agents sell generation into each of several markets
- The decision-making process for generation company agents is difficult:
  - The commodity they produce (electric power) cannot typically be stored
  - The power "transportation" system (the electric grid) follows well understood, but highly complicated, rules
  - Generation company agents have limited knowledge about the other players in the market
- The success of generation company agent decisions are not guaranteed
- Sophisticated decision making is needed…



EMCAS Has Undergone Thorough Verification and Validation Using a Variety of Techniques, for Example…

- The model was developed by a team of experienced domain experts consisting of electric power and system engineers as well as economists
- Extensive validation of the data on the existing system and planned developments and expansions in the future was conducted by checking the data with the original data sources and cross-checking data with interested third parties
- Independent subject matter experts (SMEs) from the electric utility industry were assembled (i.e., independent of the model developers) to review model assumptions and model outputs for a limited number of cases
- Comprehensive testing of plausible agent strategies was essential to obtaining valid model results:
  - It was not possible to draw general conclusions from only a handful of model runs because of the nonlinear, dynamic aspects of the agent behaviors and interactions
  - Extensive model runs served the dual purposes of verifying model behaviors that were expected, thereby increasing the confidence in the model, and discovering model behaviors that were unexpected
  - Discovering unexpected cases created focal points for further model runs and more in-depth analysis and explanation
  - This process resulted in identifying the need for hundreds of additional model runs
- All model results and the answers to the obvious questions pertaining to the model results had to be explainable in plain language or they would not be useful to decision-makers
- The model validation phase ended up taking as long as the model development phase
- In the end, however, it was generally accepted that the model was a valid one for answering a wide range of important questions pertaining to electric power deregulation

Reproducing Human Behavior

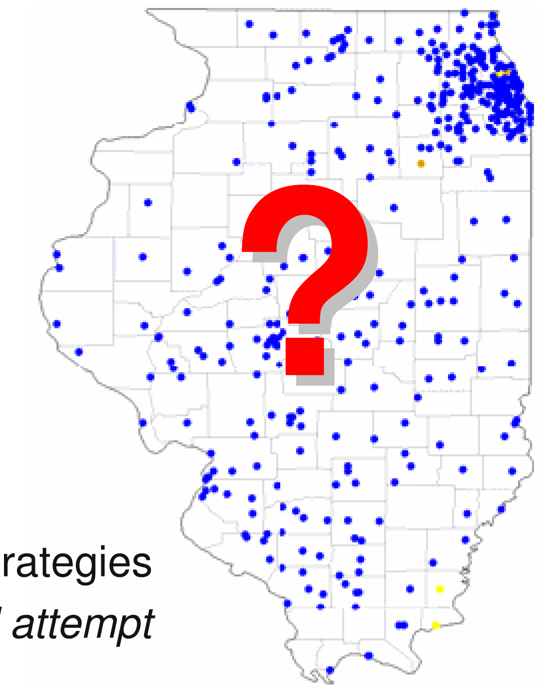


- The correlation between the programmed EMCAS agents and experimental results is $R^2 = 0.93$
- The mismatch was caused by human adaptation during the game

EMCAS Was Recently Used for an Illinois Commerce Commission (ICC) Study

- The questions under study included the following:
  - Is the transmission system adequate to support market operation?
  - Is there the potential for market power to be exerted?

    “Market power” is defined here as the ability to raise prices and increase profitability by unilateral action
- The study was designed to be:
  - exploratory, not predictive of specific outcomes,
  - an initial investigation, and
  - issue-oriented, not regulatory-oriented.
- Study cases were constructed as “electronic experiments” to study market behavior
- The experiments moved from very simple to more complex strategies
- *The study was not intended to imply that any company would attempt to exercise market power*
- The study was only an initial mapping of ***possible*** market bidding…



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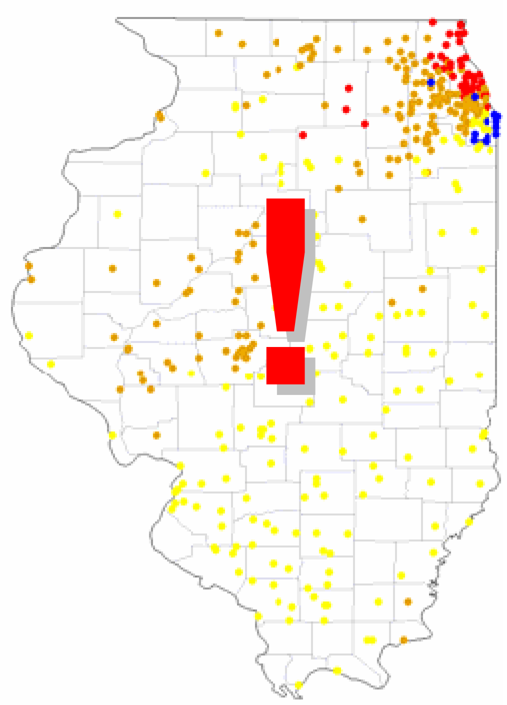
These are Some Selected Observations Under the Study's Assumed Conditions…

- Is the transmission system adequate to support market operation?

  Under the study's assumptions, the transmission system is adequate for most hours, but will show signs of congestion about 5% of the time.

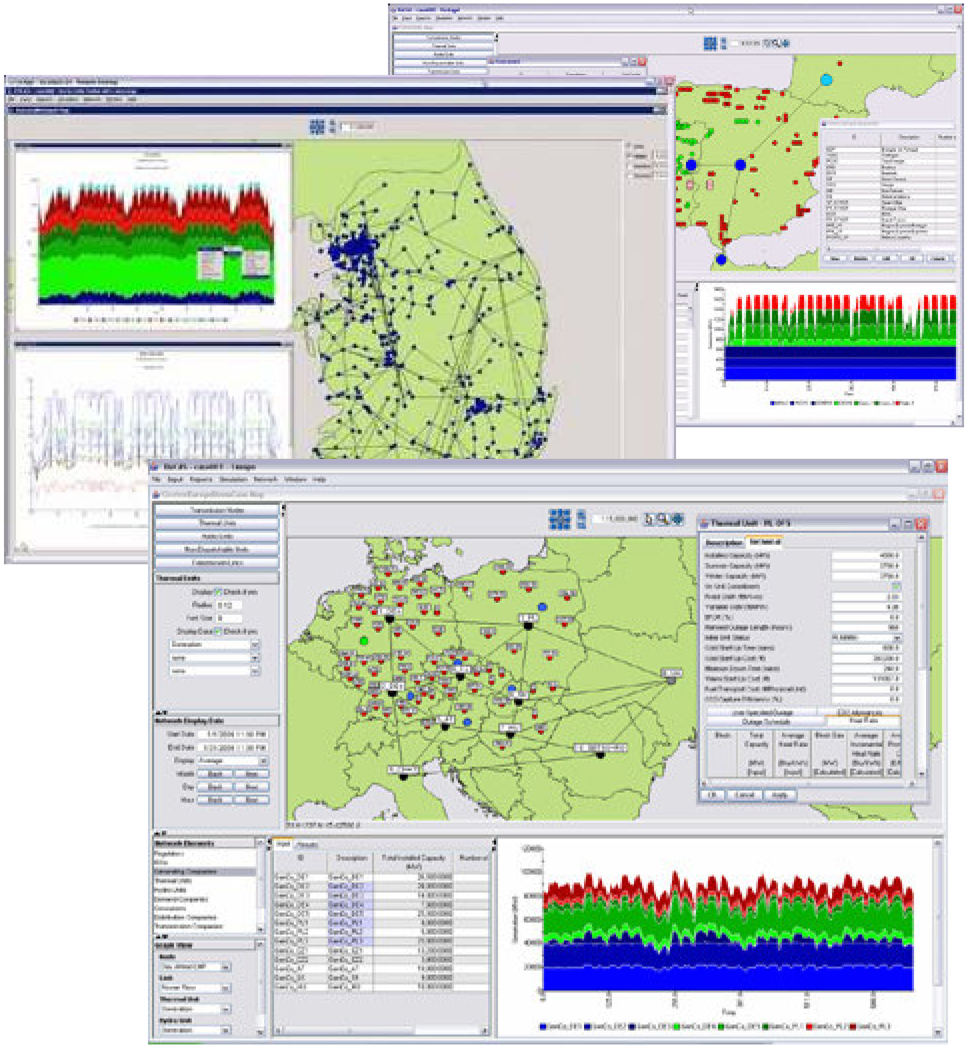
- Is there the potential for market power to be exerted?

  Under the study's assumptions, there is the <u>potential</u> for specific companies to exercise market power (i.e., raise prices and increase profitability by unilateral action) and raise consumer costs under selected conditions, particularly when there is transmission congestion.



EMCAS is Increasingly Used to Study Market Restructuring Issues Worldwide

- Clients include:
  - Regulatory institutions interested in market design and consumer impact issues
  - Transmission companies and market operators studying system and market performance
  - Generation companies analyzing strategic company issues
- Model implementations for clients in:
  - U.S.
  - Europe
  - Asia



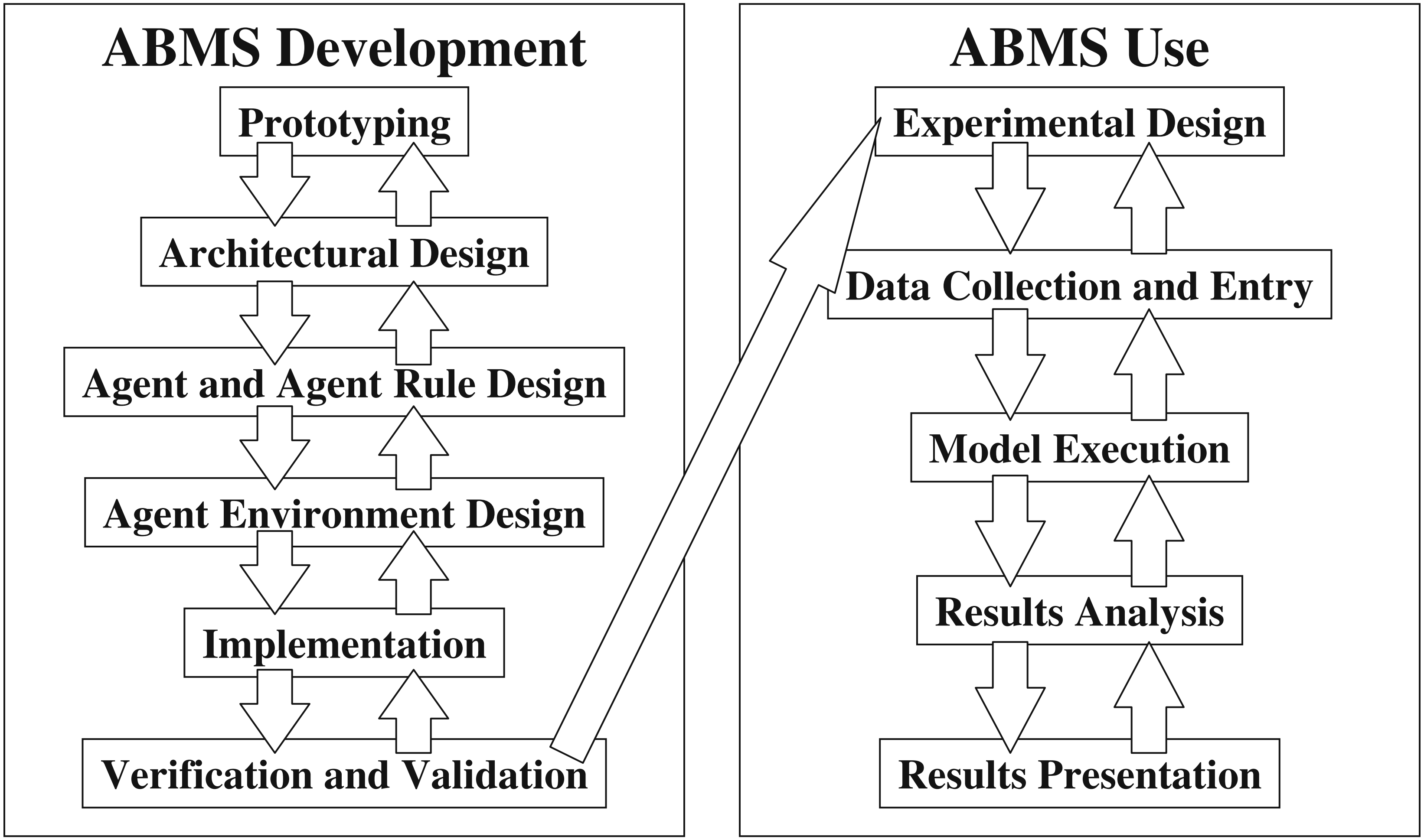
How to do agent-based modeling?

Get a Theory!

Social agent-based modeling & simulation relies on the theory of individual behavior.

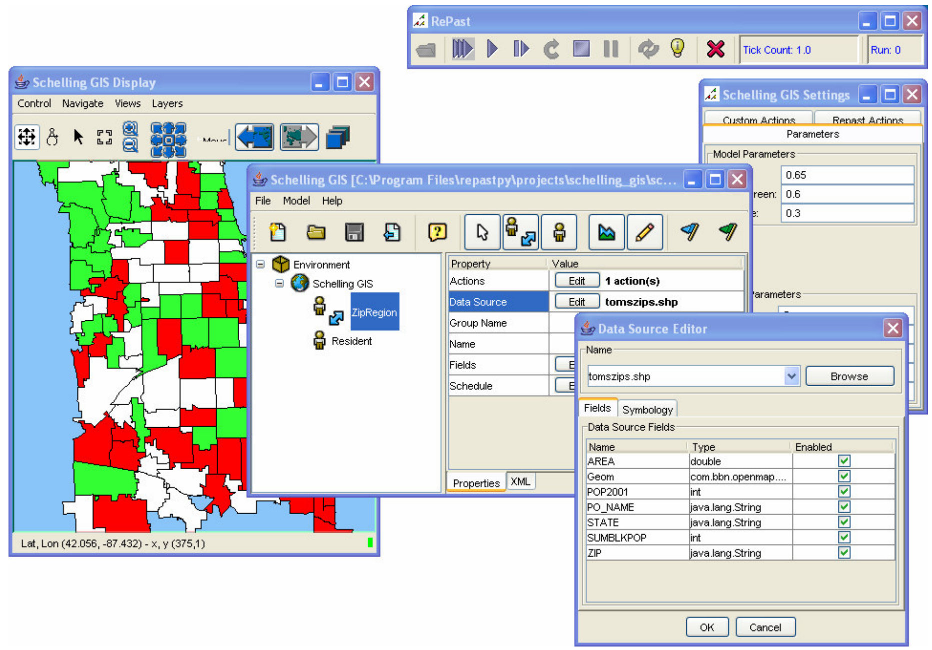
- Agent rules are based on theories of the individual
  - Rational Individual Behavior: Individuals collaborate with others when it is in their best economic interest to do so, and collaboration allows them to survive
  - Bounded Rationality: Individuals’ reasoning regarding goals is progressively refined by means of procedures that account for the limited knowledge and abilities of the decision maker
- Based on simple rules, ABMS can be used to study how organizational structures form and evolve

The ABMS Business Process



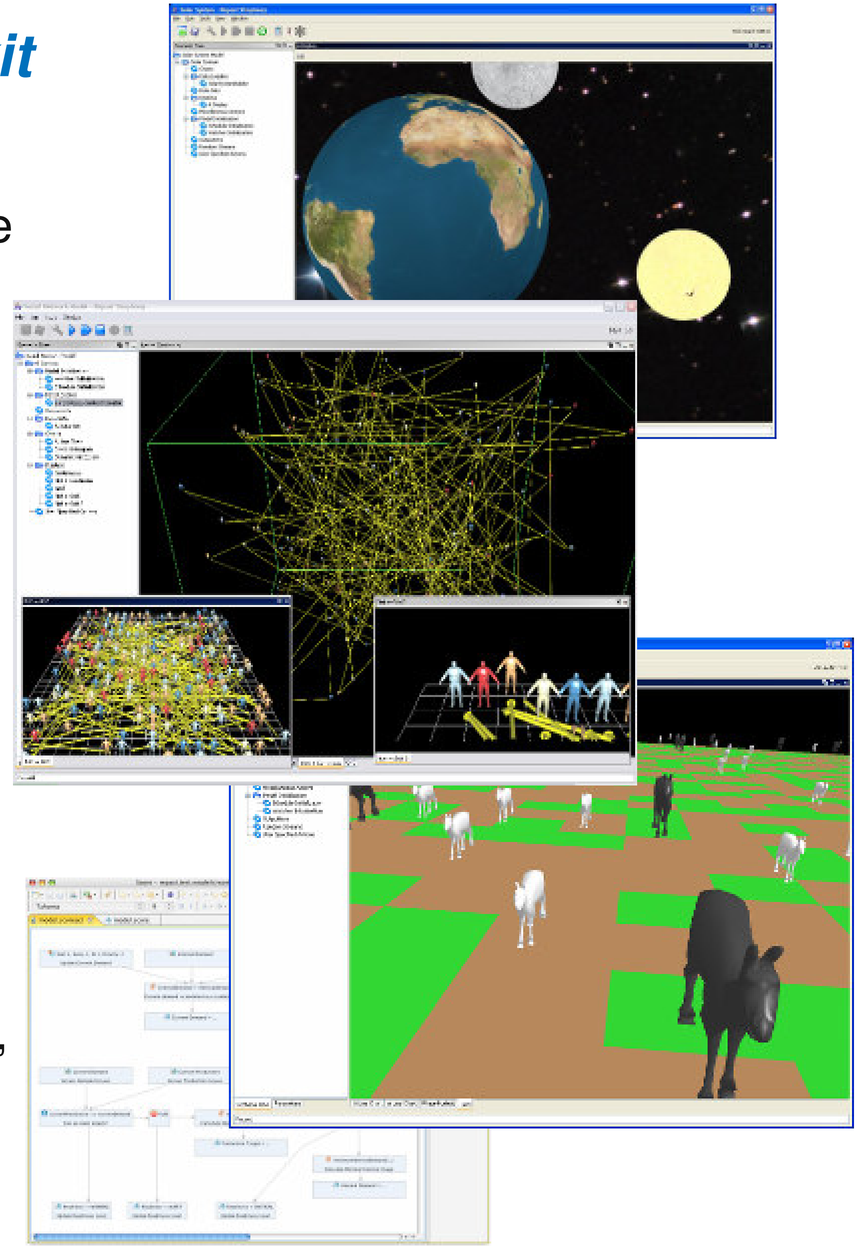
Example ABMS Platform: The free and open source Repast toolkit

- The REcursive Porous Agent Simulation Toolkit (Repast) is available in pure Java and pure Microsoft.NET C# framework forms:
  - Repast Simphony (Repast S)
  - Repast for Java (Repast J)
  - Repast for Microsoft .NET framework (Repast .NET)
  - Repast for Python Scripting (Repast Py)
  - Repast Agent Analyst for ESRI ArcGIS
- Repast focuses on social simulation, but can be used for any domain



Repast is a Powerful ABMS Toolkit

- Repast has many features:
  - Automated connections to enterprise data sources
  - Automated connections to powerful external programs for statistical analysis and visualization of model results
  - Cross-platform pure Java models
  - Built-in 2D, 3D, and geographical information systems (GIS) support and tools
  - Built-in adaptation tools
  - Built-in systems dynamics modeling
- More information on Repast, as well as free downloads, can be found at the Repast development team's home page, http://repast.sourceforge.net/



What Useful Information Can Such Agent Models Give to Decision Makers?

- Understand and predict agent behaviors
- Anticipate market dynamics, structures, and possible evolutionary paths
  - Will a small number of firms tend to dominate?
  - Will change come quickly?
  - Will the market always be in a state of turbulence?
- Recognize disequilibrium situations and their causes
- Identify sources of uncertainty

When agent modeling?

- When there is a natural representation as agents
  - When there are decision and behaviors that can be defined discretely (with boundaries)
  - When it is important that agents adapt and change their behavior
  - When it is important that agents learn and engage in dynamic strategic behavior
  - When it is important that agents have a dynamic relationships with other agents, and agent relationships form and dissolve
  - When it is important that agents form organizations and adaptation and learning are important at the organization level
  - When it is important that agents have a spatial component to their behaviors and interactions
- When the past is no predictor of the future
- When scale-up to arbitrary levels is important
- When process structural change needs to be a result of the model, rather than an input to the model

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Some Conclusions:

Agent-based modeling…

- Represents a major paradigm shift in the view of the world and how to understand and model it
  - A third way of doing science?
- Is a multidisciplinary field requiring a reorganization of traditional analytical approaches
- Requires integration of interdependent processes
  - Theory
  - Modeling and computational methods
  - Practical approaches to application
- Is an exciting area for new computational approaches
- Has some grand challenges

As a Note, Argonne Sponsors a Conference and a Training Course to Promote CAS Development and Applications

Agent 2007 Conference on Complex Interaction and Social Emergence
November 15-17, 2007, with Northwestern University, Evanston IL USA

Questions?

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The End

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